10.0 SUMMARY AND CONCLUSIONS

The preceding sections of this report provide extensive data describing the static and ELF time-varying magnetic field and ELF electric field environments in a variety of widely-varying transportation systems. In each system (and often within different vehicles of the same system), magnetic fields differ in frequency distribution, temporal distribution, and spatial distribution. Hence, looking at summary descriptors of field intensity appears to dismiss other possibly important characteristics of the field. That is not the authors intent in this summary discussion. The following comparisons of field levels are in no way intended to trivialize other aspects of the field discussed more fully in preceding sections.

10.1 Summary of Magnetic Field Levels

Magnetic fields have large spatial variability in all transportation systems and large temporal variability in most. Table 10-1 shows the magnitude of the magnetic field in various frequency bands averaged across a wide range of passenger-relevant locations and a full spectrum of operating conditions. The maximum recorded field level in each transportation system is also tabulated, but placed in parenthesis. These maximum values represent the highest recorded field level at any location and any instant in time. Since thousands of measurements were made in some transportation systems, the maximum field levels represent rare events which may have no particular significance except to identify the wide range of field variability possible in each system. Minimum field levels are not tabulated because, in most cases, they are essentially zero. The reader is encouraged to consult the information contained in the body of this report for more complete system-by-system descriptions of the spatial and temporal variability in magnetic field levels.

Static magnetic fields are comparable in all ten transportation systems which is not unexpected because these fields arise predominantly from the natural magnetism of the earth. There is some suggestion in the data that static magnetic fields are produced at some ankle-level locations in the electric cars, trucks, buses, and commuter train. All of those vehicles make use of direct electric current. Those artificially generated static (direct current) fields do not add appreciably to the average total static field environment of the vehicles but do increase the temporal and spatial variability of the static field. However, the variability of the static fields in those vehicles using dc current is not dramatically inconsistent with the static field variability of other systems which do not use dc current.

To facilitate visualization of the differences in time-varying field levels in the ten transportation systems, the average and maximum time-varying field levels are shown graphically in Figures 10-1 and 10-2, respectively. For each vehicle, a bar indicates

Table 10-1
Average and Maximum (in Parenthesis) Magnetic Field Levels
Measured in Ten Transportation Systems

Transportation System	Static 0 Hz mG	ELF Frequencies 5-3000 Hz mG	Low, Sub-Power Freq. 5-55 Hz mG	Power Frequency 60 Hz mG	Power Harmonics 65-300 Hz mG	High ELF Frequencies 305-3000 Hz mG
Ferry Boat	511 (760)	0.6 (3.3)	0.2 (1.0)	0.4 (3.1)	0.2 (1.2)	0.1 (0.3)
Escalators	557 (958)	1.5 (61.4)	1.3 (60.1)	0.4 (3.2)	0.2 (10.5)	0.1 (0.3)
Moving Walkways	576 (1218)	3.7 (200.0)	3.1 (195.4)	1.2 (12.4)	0.7 (37.2)	0.3 (19.0)
Conventional Cars and Light Trucks	321 (968)	5.7 (124.5)	5.5 (124.2)	0.9 (19.4)	0.8 (13.6)	0.4 (7.8)
Electric Cars and Light Trucks						
FUDS on a Dynamometer	408 (1286)	5.7 (80.8)	3.4 (56.1)	0.9 (12.5)	3.6 (79.9)	1.0 (8.6)
Driving on a Test Track	388 (1041)	5.7 (93.5)	4.8 (92.7)	0.8 (15.3)	1.9 (24.5)	0.7 (6.9)
Jetliner	552 (669)	13.6 (212.5)	0.6 (3.5)	0.0 (0.6)	0.2 (8.1)	13.5 (212.4)
Shuttle Tram (AC Electric)	470 (835)	13.7 (90.4)	10.7 (88.5)	5.5 (29.0)	3.0 (14.4)	1.2 (7.0)
Conventional Transit Bus	401 (1124)	16.8 (145.7)	16.4 (144.2)	0.9 (14.2)	1.9 (21.3)	2.1 (24.8)
Electric Shuttle Bus	381 (808)	20.4 (487.8)	14.7 (486.7)	0.8 (38.8)	8.9 (220.5)	1.6 (10.7)
Commuter Train (AC Electric)	538 (1969)	49.6 (799.3)	18.5 (453.5)	34.2 (738.8)	14.6 (340.3)	5.9 (48.7)

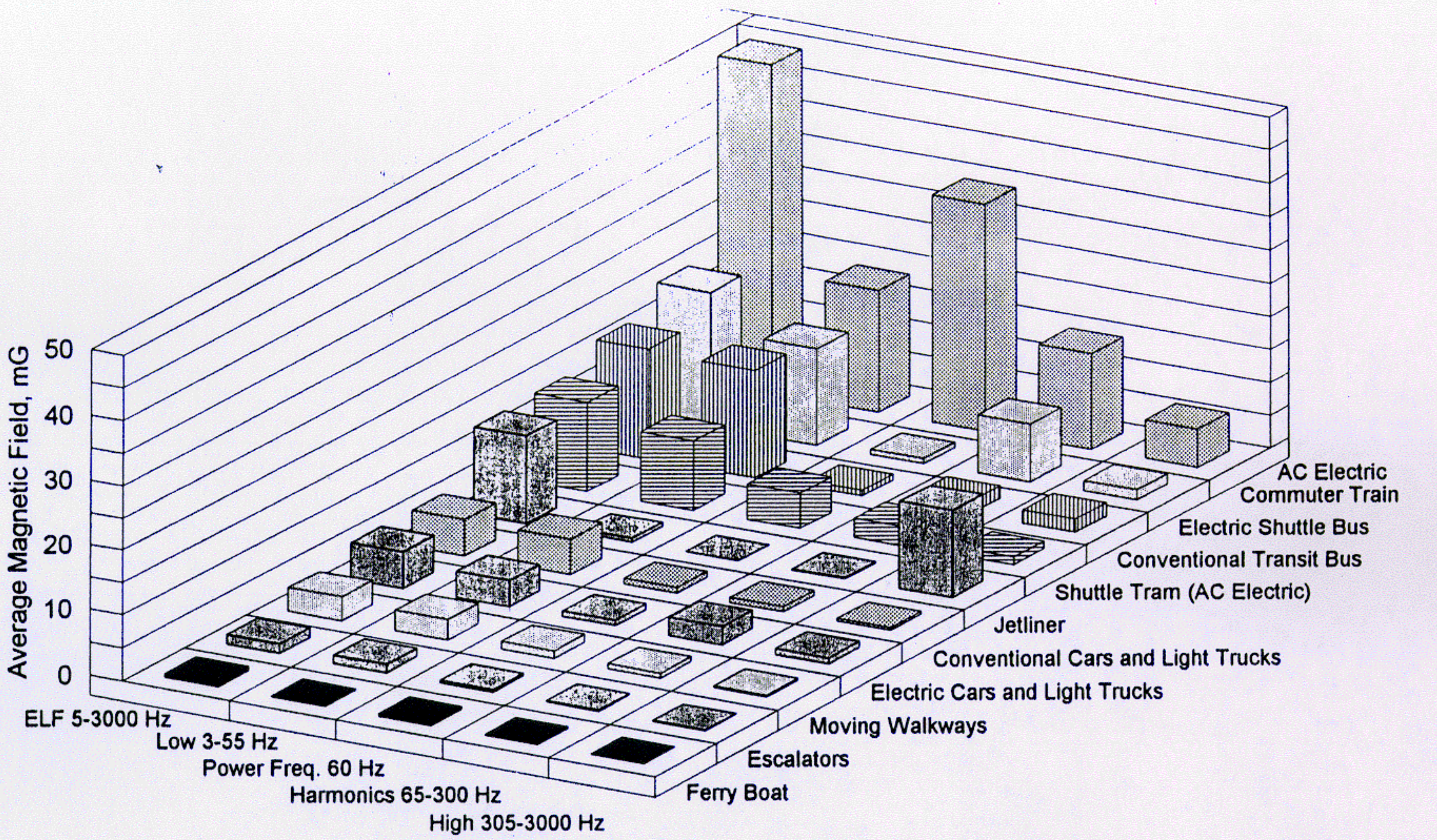

Figure 10-1 Average, Time-Varying Magnetic Field Levels in Ten Transportation Systems for Selected Frequency Bands.

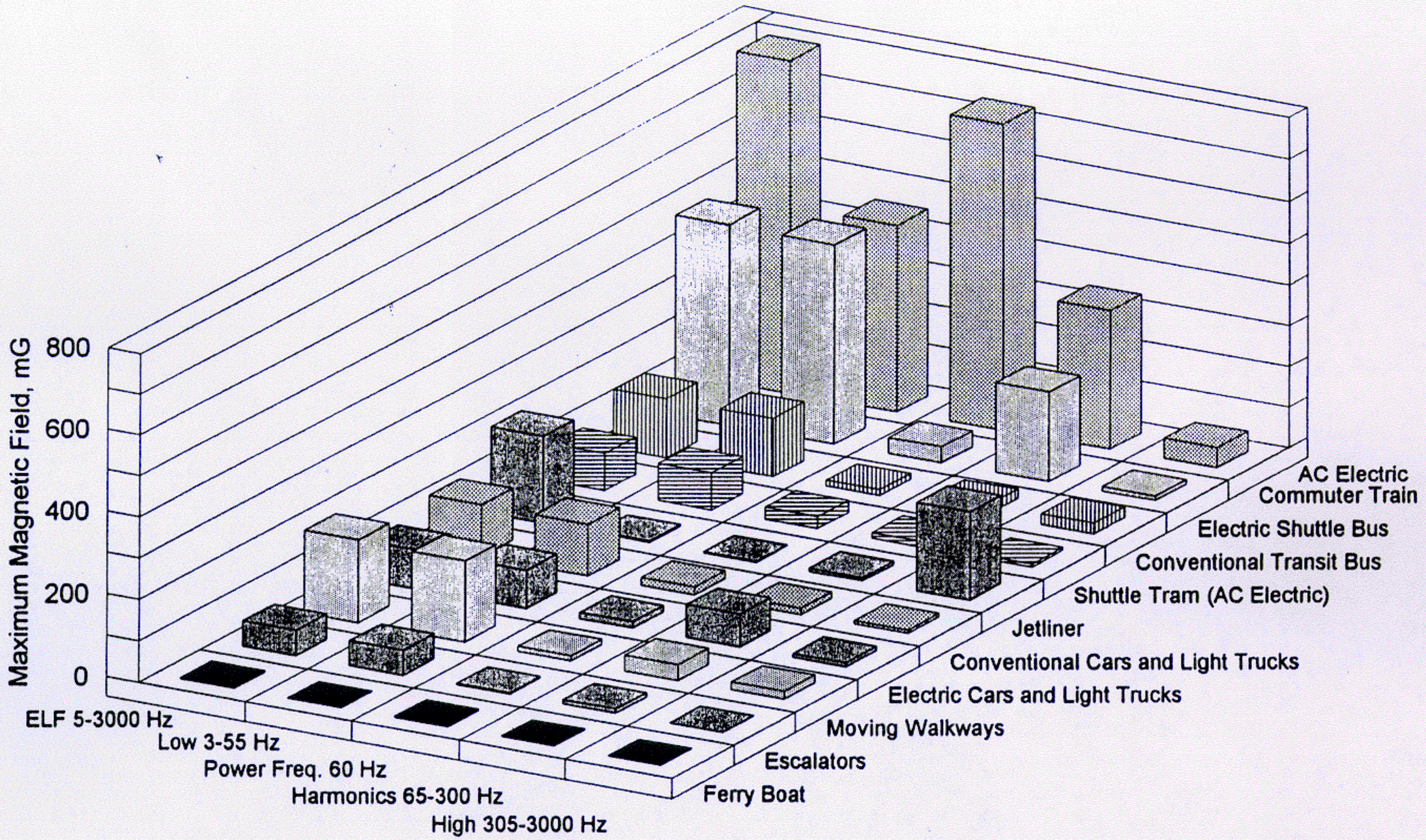

Figure 10-2 Maximum Time-Varying Magnetic Field Levels in Ten Transportation Systems for Selected Frequency Bands.

the total ELF field (5 Hz to 3 kHz) as well as the field level in four sub-bands. In this way, Figures 10-1 and 10-2 not only compare field levels between vehicles, but also provide a rudimentary indication of the frequency distributions of those fields.

In most of the ten transportation systems, the ELF magnetic fields appear primarily in the low range of frequencies below the normal 60 Hz power frequency (the sources and characteristics of those low frequency fields are summarized in the next subsection). Notable exceptions to that trend are the jetliner and the commuter train. The train has low frequency levels comparable to those in other large vehicles. However, they are eclipsed by the larger 60 Hz and harmonic fields.

In the case of the jetliner, the sources of low frequency fields are absent due to the high speed of its engines, the absence of ferromagnetic parts in its engines and airframe, and its operation away from ferromagnetic objects which severely perturb the geomagnetic field. In the jetliner, the major field source is the 400 Hz electric power wiring and electric devices such as lights in the cabin.

Sixty-hertz power frequency fields are only a major component of the magnetic field environment of the airport shuttle tram and the commuter train. Those vehicles are unique among the systems tested in that electric power for the on board propulsion systems is delivered to the vehicle in the form of 60 Hz current from a third rail system and a catenary system, respectively. The 60 Hz magnetic fields arise from both the power delivery system and on board wiring and equipment which utilize the 60 Hz power.

Time-varying magnetic fields in the power harmonics (65-300 Hz) and high ELF frequency (305-3000 Hz) bands are elevated in the vehicles which make use of on board electric propulsion systems, namely the electric cars, trucks and bus, the airport shuttle tram, and the commuter train. Those fields appear to result from power electronic equipment and associated wiring which convert dc electric power from vehicle batteries or 60 Hz electric power from supply circuits to other frequencies need for propulsion and other on board systems.

Electric highway vehicles have ELF field levels similar to their conventional internal combustion counterparts. Low frequency fields from similar sources dominate in both types of vehicles. Although higher frequency (greater than 60 Hz) fields are, on average, only a minor part of the total field environment, those components are markedly higher in some electric vehicles than their conventional counterparts. In those vehicles, the magnetic field sources tend to be localized and usually most intense near the ankles of the traveler.

10.2 Summary of Electric Field Levels

ELF electric fields are essentially nonexistent in most transportation systems. The notable exception is the commuter train which is powered from a high voltage (27 kV) 60 Hz overhead catenary system. Chest-level electric fields in the commuter train were 60 Hz with negligible harmonic distortion. They ranged from near zero to 18 v/m, averaging 4.6 v/m.

The only detectable time-varying electric fields in other vehicles were low frequency fields associated with the movement of passengers or test personnel near the measurement site. Static electric charge on synthetic clothing and other belongings produce a static electric field. When those objects move around the vehicle, there is an associated time-varying component consisting of very low frequency components. Those were detected and found to be typically in the range of 3 to 30 v/m.

10.3 Magnetic Field Sources

Source identification was not an intended component of this effort. Nevertheless, the comprehensive field characterization provided by the magnetic field waveform sampling techniques employed provides valuable insight to significant sources of magnetic fields in transportation systems. The following paragraphs identify the principal sources identified and some salient characteristics of the fields which they generate.

<u>10.3.1 Moving Magnetized Mechanical Components</u>

Nearly all of the transportation systems use ferromagnetic components in their engines and drive trains. Many of those components have some apparently unintentional residual magnetism. When those magnetized components move, they produce time-varying magnetic fields. Periodic magnetic fields were observed from rotating engine and drive train components in both conventional and electric vehicles. A common and significant source is residual magnetism in the steel belts of radial tires on personal highway vehicles (cars and light trucks). The frequency of the fields originating from these sources is proportional to either vehicle or engine speed and most typically in the range of frequencies below 100 Hz. This was the dominant source of magnetic fields in many vehicles.

Linearly moving magnetized components was a dominant time-varying magnetic field source on escalators and moving sidewalks. Components of both the handrail and tread are magnetized and produce time-varying fields as they return the opposite direction beneath the tread.

10.3.2 Movement Through Non-Uniform Static Fields

The geomagnetic field which surrounds all transportation equipment is highly perturbed by ferromagnetic objects such as steel in highway bridges, tunnel reinforcing steel along underground tramways, structural steel in and near escalators and moving sidewalks, or even parked or passing transportation vehicles. Furthermore, any of those ferromagnetic objects can have their own magnetism. As a result, there are frequently large spatial gradients in the static field along the route of travel of a transportation vehicle. There is a significant transient field in the vehicle as it passes through those gradients. The magnitude of the time-varying components in the ELF band is dependant upon the steepness of the gradient and rate of passage through it. However, since the rate of passage is usually rather low compared to frequencies in the ELF band, the largest components of the time-varying magnetic field are almost always in the lowest few frequency bins (5 Hz and 10 Hz) and decrease in intensity rapidly at higher frequencies. Magnetic fields from this source demonstrate large temporal variability, contributing significantly to maximum field levels but having lesser effect on average or median levels.

10.3.3 Anisotropic Shielding by Vehicle Body

In most of the transportation systems examined, the vehicle was constructed using ferromagnetic materials which perturb and generally attenuate the geomagnetic field as it enters the vehicle. The extent of static field perturbation and shielding is highly dependant upon location in the vehicle and orientation of the vehicle with respect to the geomagnetic field vector. If the orientation of the vehicle changes as when negotiating a turn, the magnitude of the static field changes at most locations in the vehicle giving rise to time-varying components with characteristics similar to those described in Section 10.3.2 above. In fact, this anisotropic shielding by the vehicle body typically enhances the low frequency fields generated by traveling through a spatially perturbed magnetic field because, in the area of perturbation, the static field orientation often changes dramatically over short distances.

10.3.4 On Board Electric Propulsion System

Vehicles having an on board electric propulsion system such as electric cars, trucks, buses, airport trams and electric commuter railroad vehicles all contain electric motors and the electric power control circuitry and devices necessary to regulate the traction power needs of the vehicle. Previous measurements

[1] in electric power guided ground transportation systems demonstrated the wide range of field conditions which could be produced by these devices. All of the electric powered transportation vehicles examined in this study used newer power semiconductor technology to control electric power to the traction motors. Some used ac traction motors rather than dc motors as has been done historically making use of newer electronic inverter technology.

Vehicles in this class typically exhibited magnetic fields with a fundamental frequency component in the vicinity of 100 to 200 Hz from the electronic converters but usually had significant harmonic fields throughout much of the ELF range. This accounts for the elevated fields in the power harmonics frequency range (65-300 Hz) and high ELF frequency range (305-3000 Hz) seen for these vehicles in Figures 10-1 and 10-2.

Some vehicles such as the commuter train vehicles use ac traction motors. To control the speed of travel, the electronic traction power control invertors produce ac power at variable frequencies. (The speed of the motor is proportional to the frequency of the applied electric power.) In these vehicles, speed-dependant magnetic fields (in the frequency range from zero to approximately 100 Hz) are observed in some locations.

10.3.5 Stationary Electric Propulsion System

People-movers such as moving walkways, escalators, and elevators typically have stationary electric drive systems which today usually operate from 60 Hz power. Measurements carried out in this project suggest that these stationary power sources are at best very modest field sources creating 60 Hz magnetic fields which are difficult to detect in the presence of ambient 60 Hz fields from other sources.

10.3.6 Power Delivery Circuits

Vehicles such as the airport tram and the electric commuter railroad cars receive electric power from a third rail system or overhead catenary system. Both of the systems tested in this project received ac power at 60 Hz. Other systems use dc power or ac power at other frequencies [1]. To facilitate electric power connections with the moving vehicle while avoiding short circuits, the conductors of the power supply circuits must have reasonable separation. Smaller, three-phase ac systems like the airport tram have a "third rail" system in the center of the guide way with three power conductors separated by approximately 6 inches. Large rail systems have the overhead catenary supply conductor separated approximately 15 feet from the power return circuit. In both cases, the large spacing between the power supply conductors makes them effective magnetic field sources which contribute to the magnetic field within the vehicle. The time-varying magnetic field in the commuter train was principally 60 Hz. That component averaged 32.4 mG which is consistent with that which arose from catenary-track magnetic fields in other 60 Hz electric railroads (52.0 mG Amtrak Northeast Corridor, 18.2 mG New Jersey Transit Long Branch Line [1]).

10.3.7 On Board Accessories

Magnetic fields from on board accessories such as passenger lighting, ventilating fans, and vehicle headlight controllers were seen on many vehicles. In most cases, these fields are highly localized and often have very specific frequency signatures.

10.3.8 External Field Sources

External magnetic fields from sources unrelated to the transportation system contribute to the field environment within the system. The geomagnetic field was the principal source of static fields in all vehicles. Sixty-hertz fields from powerlines along the roadway were the major source of 60 Hz fields in conventional vehicles which were tested on a range of road types. Those tests suggest that an average 60 Hz magnetic field of about 0.9 mG would be found in any highway vehicle from powerlines along the roadway.